

# **Possible studies of tensor-polarized structure functions for a spin-one hadron at Fermilab Main Injector**

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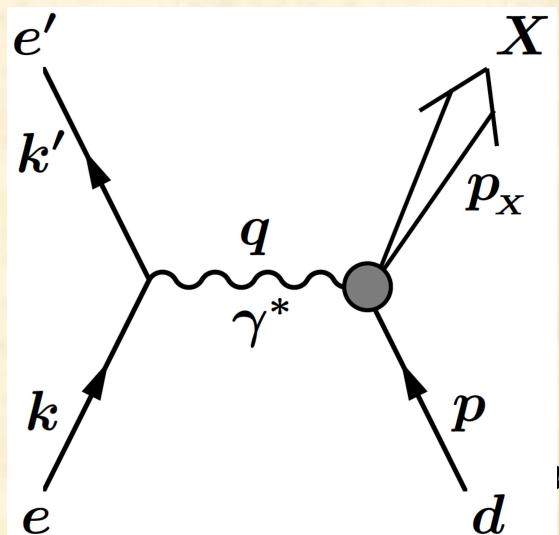
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<http://research.kek.jp/people/kumanos/>

**Refs.** (1) **SK and Qin-Tao Song, Phys. Rev. D94 (2016) 054022.**  
(2) W. Cosyn, Yu-Bing Dong, SK, M. Sargsian, to be submitted for publication.

**Joint Fermilab-KEK Theory Meeting in 2016**  
**Fermilab, Batavia, Illinois, USA, September 26-30, 2016**  
[http://home.fnal.gov/~pjfox/KEK\\_FNAL\\_2016/KEK-FNAL2016.html](http://home.fnal.gov/~pjfox/KEK_FNAL_2016/KEK-FNAL2016.html)

**September 30, 2016**

# Introduction to Structure functions of spin-1 hadron

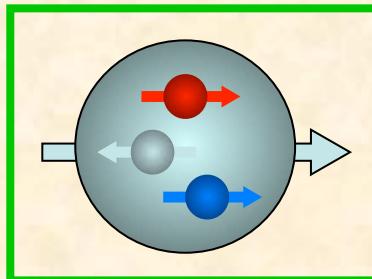


**Stable spin-1 target**  
= deuteron,  ${}^6\text{Li}$ , ...

You may be interested in applying  
for other spin-1 particles,  $q$ ,  $\gamma$ , ...

# Origin of nucleon spin

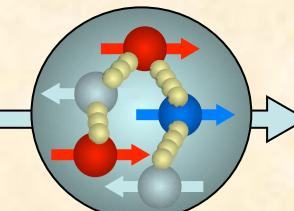
“old” standard model



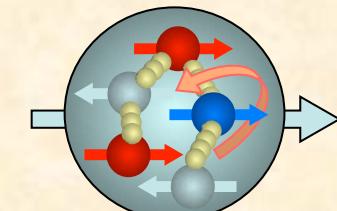
$$p_{\uparrow} = \frac{1}{3\sqrt{2}} (uud [2 \uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow] + \text{permutations})$$

$$\Delta q(x) \equiv q_{\uparrow}(x) - q_{\downarrow}(x)$$

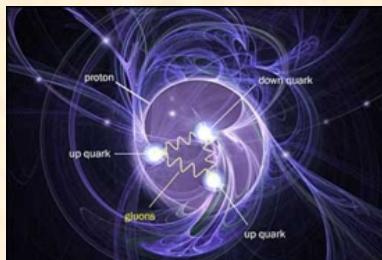
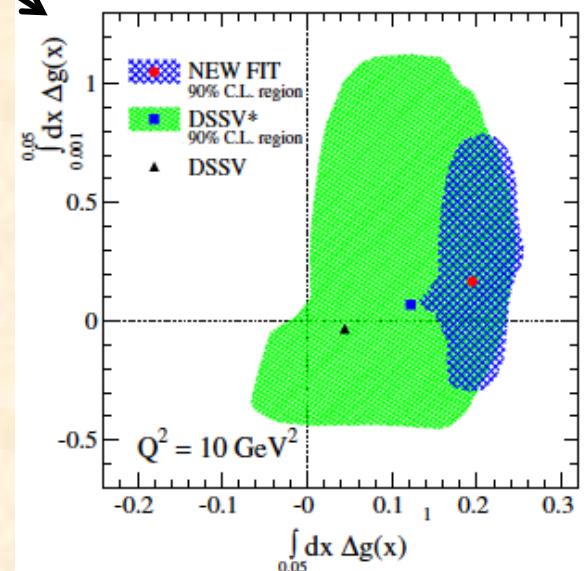
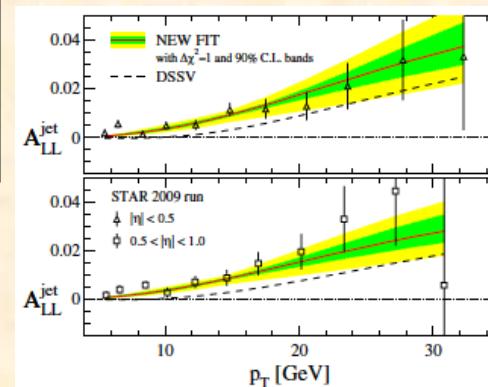
$$\Delta\Sigma = \sum_i \int dx [\Delta q_i(x) + \Delta \bar{q}_i(x)] \rightarrow 1 \text{ (100%)}$$



gluon spin



angular momentum  
→ tomography

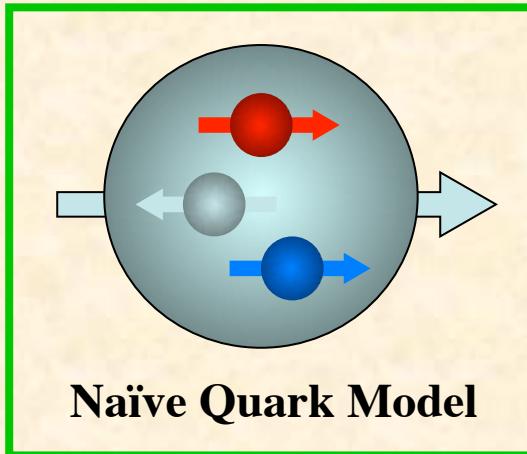


CNN (2014)

Scientific American (2014)

$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta g + L_{q,g}$$

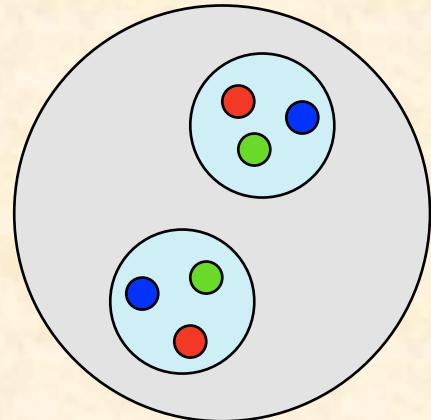
## Nucleon spin



Naïve Quark Model

“old” standard model

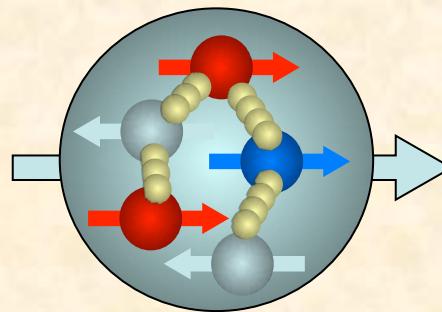
## Tensor structure



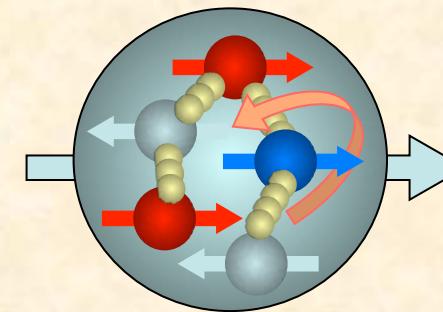
only S wave

$$\mathbf{b}_1 = 0$$

Almost none of nucleon spin  
is carried by quarks!



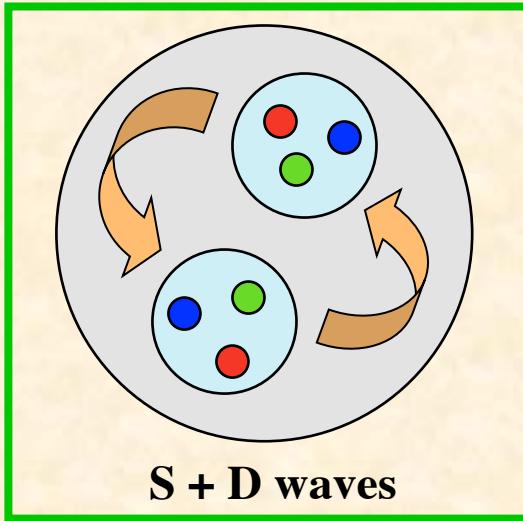
Sea-quarks and gluons?



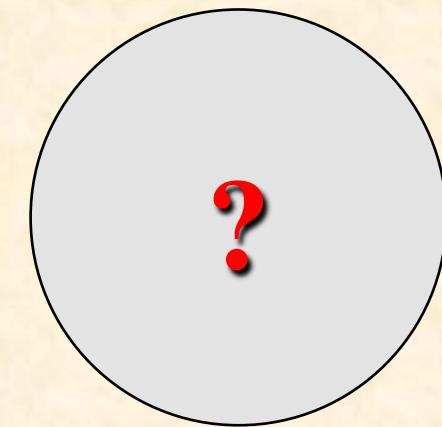
Orbital angular momenta ?

$\mathbf{b}_1$  (e.g. deuteron)

Tensor-structure puzzle?



standard model     $\mathbf{b}_1 \neq 0$

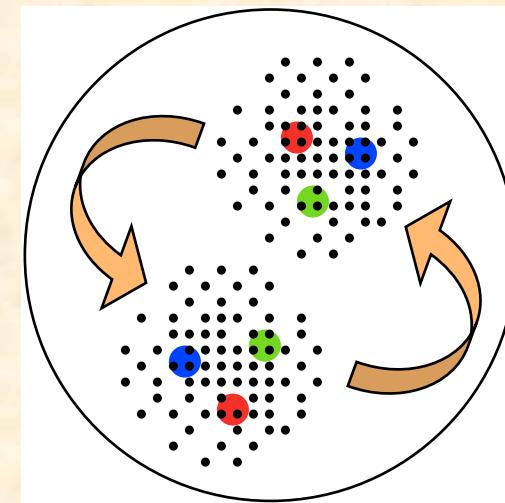
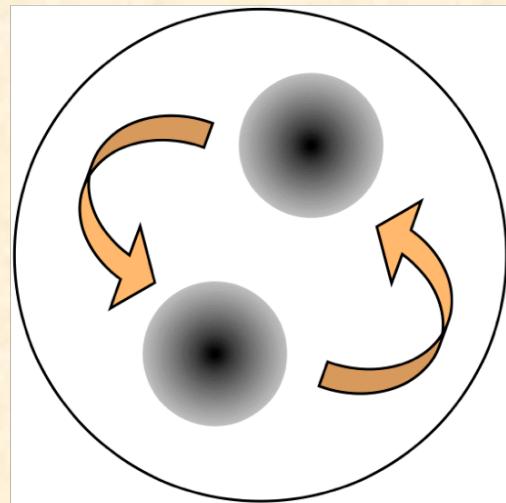


$\mathbf{b}_1^{\text{experiment}} \neq \mathbf{b}_1^{\text{"standard model"}}$

# Roles of quark degrees of freedom in deuteron

The deuteron is a well-studied system  
by hadronic degrees of freedom

If we find that the deuteron is not simple bound system of a proton and a neutron (namely if we find an exotic quark signature), it is an important discovery and it could open a new field of spin physics (and possibly a new topic of nuclear physics), which is very different from current nucleon-spin physics.



# Situation

- **Spin structure of the spin-1/2 nucleon**

**Nucleon spin puzzle:** This issue is not solved yet,  
but it is rather well studied theoretically and experimentally.

- **Spin-1 hadrons (e.g. deuteron)**

There are some theoretical studies especially on tensor structure  
in electron-deuteron deep inelastic scattering.

→ HERMES experimental results → JLab experiment

No experimental measurement has been done for  
hadron ( $p$ ,  $\pi$ , ...) - polarized deuteron processes.

→ Fermilab measurement?

Hadron facility (J-PARC, RHIC, COMPASS, GSI, ...) experiment ?

# Personal studies on tensor structure of the deuteron

- **Sum rule for  $b_1$**   
F. E. Close and SK, Phys. Rev. D42 (1990) 2377.
- **Polarized proton-deuteron Drell-Yan: General formalism**  
M. Hino and SK, Phys. Rev. D59 (1999) 094026.
- **Polarized proton-deuteron Drell-Yan: Parton model**  
M. Hino and SK, Phys. Rev. D60 (1999) 054018.
- **Extraction of  $\Delta\bar{u}/\Delta\bar{d}$  and  $\Delta_T u/\Delta_T d$  from polarized pd Drell-Yan**  
SK and M. Miyama, Phys. Lett. B497 (2000) 149.
- **Projections to  $b_1, \dots, b_4$  from  $W_{\mu\nu}$**   
T.-Y. Kimura and SK, Phys. Rev. D 78 (2008) 117505.
- **Tensor-polarized distributions from HERMES data**  
SK, Phys. Rev. D82 (2010) 017501.
- **Tensor-polarization asymmetry in pd Drell-Yan**  
SK and Qin-Tao Song, Phys. Rev. D94 (2016) 054022.
- **Convolution calculation for  $b_1$**   
to be submitted for publication

JLab experiment ~2019, Fermilab pd Drell-Yan?, ...

Motived by the following works.

Hoodbhoy-Jaffe-Manohar (1989)

Polarized deuteron acceleration at RHIC:  
E. D. Courant, Report BNL-65606 (1998)

HERMES measurement on  $b_1$  (2005)

Future possibilities  
at JLab, Fermilab, J-PARC,  
RHIC, ILC, ...

JLab PAC-38 proposal, PR12-11-110,  
J.-P. Chen *et al.* (2011) → approved!  
Fermilab-E1039, under consideration.

# Cross section for $e + \vec{d} \rightarrow e' + X$

$$d\sigma = \frac{1}{4\sqrt{(k \cdot p)^2 - m^2 M_N^2}} \sum_{pol} \sum_X (2\pi)^4 \delta^4(k + p - k' - p_X) |M|^2 \frac{d^3 k'}{(2\pi)^3 2E},$$

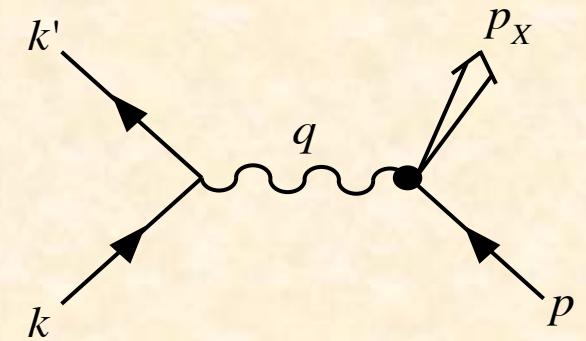
$$M = e \bar{u}(k', \lambda') \gamma_\mu u(k, \lambda) \frac{g^{\mu\nu}}{q^2} \langle X | e J_\nu^{em}(\mathbf{0}) | p, \lambda_N \rangle$$

$$\begin{aligned} \sum_{pol} \sum_X (2\pi)^4 \delta^4(k + p - k' - p_X) |M|^2 &= \frac{e^4}{Q^2} \sum_{\lambda, \lambda'} \sum_{\lambda_N} \sum_X (2\pi)^4 \delta^4(k + p - k' - p_X) \\ &\times \left[ \bar{u}(k', \lambda') \gamma^\mu u(k, \lambda) \right]^* \left[ \bar{u}(k', \lambda') \gamma^\nu u(k, \lambda) \right] \langle p, \lambda_N | J_\mu^{em}(\mathbf{0}) | X \rangle \langle X | J_\nu^{em}(\mathbf{0}) | p, \lambda_N \rangle \\ &= \frac{(4\pi\alpha)^2}{Q^2} 4\pi M_N L^{\mu\nu} W_{\mu\nu} \end{aligned}$$

**Lepton tensor:**  $L^{\mu\nu} = \sum_{\lambda, \lambda'} \left[ \bar{u}(k', \lambda') \gamma^\mu u(k, \lambda) \right]^* \left[ \bar{u}(k', \lambda') \gamma^\nu u(k, \lambda) \right] = 2 \left[ k^\mu k'^\nu + k'^\mu k^\nu - (k \cdot k' - m^2) g^{\mu\nu} \right]$

**Hadron tensor:**  $W_{\mu\nu} = \frac{1}{4\pi M_N} \sum_{\lambda_N} \sum_X (2\pi)^4 \delta^4(k + p - k' - p_X) \langle p, \lambda_N | J_\mu^{em}(\mathbf{0}) | X \rangle \langle X | J_\nu^{em}(\mathbf{0}) | p, \lambda_N \rangle$

$$d\sigma = \frac{2M_N}{s - M_N^2} \frac{\alpha^2}{Q^4} L^{\mu\nu} W_{\mu\nu} \frac{d^3 k'}{E'}$$



# Electron scattering from a spin-1 hadron

P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571.  
 [ L. L. Frankfurt and M. I. Strikman, NP A405 (1983) 557. ]

$$W_{\mu\nu} = \boxed{-\mathbf{F}_1 g_{\mu\nu} + \mathbf{F}_2 \frac{p_\mu p_\nu}{v} + \mathbf{g}_1 \frac{i}{v} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + \mathbf{g}_2 \frac{i}{v^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma)} \quad \text{spin-1/2, spin-1}$$

$$\boxed{-\mathbf{b}_1 r_{\mu\nu} + \frac{1}{6} \mathbf{b}_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) + \frac{1}{2} \mathbf{b}_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} \mathbf{b}_4 (s_{\mu\nu} - t_{\mu\nu})} \quad \text{spin-1 only}$$

Note: Obvious factors from  $q^\mu W_{\mu\nu} = q^\nu W_{\mu\nu} = 0$  are not explicitly written.  $E^\mu = \text{polarization vector}$

$$v = p \cdot q, \quad \kappa = 1 + M^2 Q^2/v^2, \quad E^2 = -M^2, \quad s^\sigma = -\frac{i}{M^2} \epsilon^{\sigma\alpha\beta\tau} E_\alpha^* E_\beta p_\tau$$

$b_1, \dots, b_4$  terms are defined so that they vanish by spin average.

$$r_{\mu\nu} = \frac{1}{v^2} \left( q \cdot E^* q \cdot E - \frac{1}{3} v^2 \kappa \right) g_{\mu\nu}, \quad s_{\mu\nu} = \frac{2}{v^2} \left( q \cdot E^* q \cdot E - \frac{1}{3} v^2 \kappa \right) \frac{p_\mu p_\nu}{v}$$

$$t_{\mu\nu} = \frac{1}{2v^2} \left( q \cdot E^* p_\mu E_\nu + q \cdot E^* p_\nu E_\mu + q \cdot E p_\mu E_\nu^* + q \cdot E p_\nu E_\mu^* - \frac{4}{3} v p_\mu p_\nu \right)$$

$$u_{\mu\nu} = \frac{1}{v} \left( E_\mu^* E_\nu + E_\nu^* E_\mu + \frac{2}{3} M^2 g_{\mu\nu} - \frac{2}{3} p_\mu p_\nu \right)$$

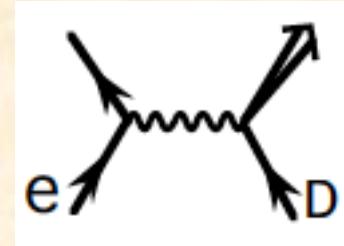
$b_1, b_2$  terms are defined to satisfy  
 $2x b_1 = b_2$  in the Bjorken scaling limit.

$2x b_1 = b_2$  in the scaling limit  $\sim O(1)$

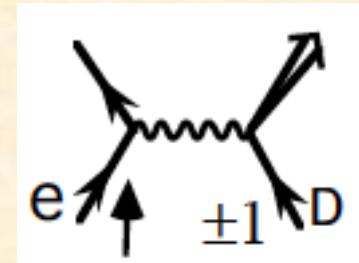
$b_3, b_4 = \text{twist-4} \sim \frac{M^2}{Q^2}$

# Structure Functions

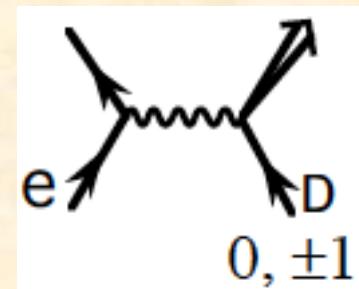
$$F_1 \propto \langle d\sigma \rangle$$



$$g_1 \propto d\sigma(\uparrow, +1) - d\sigma(\uparrow, -1)$$



$$b_1 \propto d\sigma(0) - \frac{d\sigma(+1) + d\sigma(-1)}{2}$$



note:  $\sigma(0) - \frac{\sigma(+1) + \sigma(-1)}{2} = 3\langle \sigma \rangle - \frac{3}{2} [\sigma(+1) + \sigma(-1)]$

## Parton Model

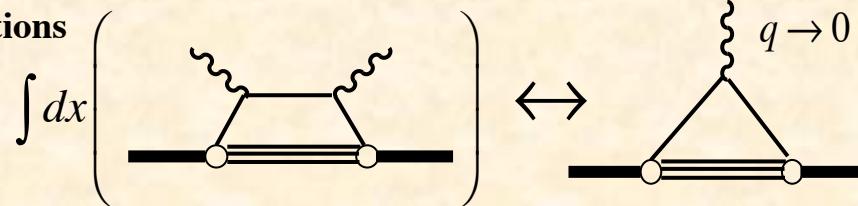
$$F_1 = \frac{1}{2} \sum_i e_i^2 (q_i + \bar{q}_i) \quad q_i = \frac{1}{3} (q_i^{+1} + q_i^0 + q_i^{-1})$$

$$g_1 = \frac{1}{2} \sum_i e_i^2 (\Delta q_i + \Delta \bar{q}_i) \quad \Delta q_i = q_{i\uparrow}^{+1} - q_{i\downarrow}^{+1}$$

$$\left[ q_{\uparrow}^H(x, Q^2) \right] \quad b_1 = \frac{1}{2} \sum_i e_i^2 (\delta_T q_i + \delta_T \bar{q}_i) \quad \delta_T q_i = q_i^0 - \frac{q_i^{+1} + q_i^{-1}}{2}$$

# Constraint on valence-tensor polarization (sum rule)

Follow Feynman's book on  
Photon-Hadron Interactions



$$\int dx b_1^D(x) = \frac{5}{18} \int dx [\delta_T u_\nu + \delta_T d_\nu] + \frac{1}{18} \int dx [8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D]$$

Elastic amplitude in a parton model

$$\Gamma_{H,H} = \langle p, H | J_0(0) | p, H \rangle = \sum_i e_i \int dx [q_{i\uparrow}^H + q_{i\downarrow}^H - \bar{q}_{i\uparrow}^H - \bar{q}_{i\downarrow}^H]$$

$$\frac{1}{2} \left[ \Gamma_{0,0} - \frac{1}{2} (\Gamma_{1,1} + \Gamma_{-1,-1}) \right] = \frac{1}{3} \int dx [\delta_T u_\nu(x) + \delta_T d_\nu(x)]$$

Macroscopically  $\Gamma_{0,0} = \lim_{t \rightarrow 0} \left[ F_c(t) - \frac{t}{3} F_Q(t) \right], \quad \Gamma_{+1,+1} = \Gamma_{-1,-1} = \lim_{t \rightarrow 0} \left[ F_c(t) + \frac{t}{6} F_Q(t) \right]$

$$\frac{1}{2} \left[ \Gamma_{0,0} - \frac{1}{2} (\Gamma_{1,1} + \Gamma_{-1,-1}) \right] = - \lim_{t \rightarrow 0} \frac{t}{2} F_Q(t)$$

$$\int dx b_1^D(x) = \frac{5}{9} \frac{3}{2} \left[ \Gamma_{0,0} - \frac{1}{2} (\Gamma_{1,1} + \Gamma_{-1,-1}) \right] + \frac{1}{18} \int dx [8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D]$$

$$= - \frac{5}{6} \lim_{t \rightarrow 0} t F_Q(t) + \frac{1}{18} \int dx [8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D]$$

$$= 0 \text{ (valence)} + \frac{1}{18} \int dx [8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D]$$

F.E.Close and SK,  
PRD42, 2377 (1990).

Intuitive derivation without calculation:  
 $\int dx b_1(x) = \text{dimensionless quantity}$   
 $= (\text{mass})^2 \cdot (\text{quadrupole moment})$

$$b_1 = \frac{1}{2} \sum_i e_i^2 (\delta_T q_i + \delta_T \bar{q}_i)$$

$$\delta_T q_i = q_i^0 - \frac{q_i^{+1} + q_i^{-1}}{2}$$

$$\delta_T q_\nu \equiv \delta_T q - \delta_T \bar{q}$$



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Constraint on tensor-polarized  
valence quarks:  $\int dx \delta_T q_\nu(x) = 0$

# Similarity to the Gottfried sum rule

SK, Phys. Rept. 303 (1998) 183.

$$\begin{aligned} S_G &= \int_0^1 \frac{dx}{x} [F_2^{\mu p}(x) - F_2^{\mu n}(x)] \\ &= \frac{1}{3} + \frac{2}{3} \int_0^1 dx [\bar{u}(x) - \bar{d}(x)] \\ &= \frac{1}{3} \quad \text{if } \bar{u} = \bar{d} \end{aligned}$$

(Gottfried sum rule)

NMC measurement (PRL 66 (1991) 2712; PRD 50 (1994) R1)

$$\int_{0.004}^{0.8} \frac{dx}{x} [F_2^{\mu p}(x) - F_2^{\mu n}(x)] = 0.221 \pm 0.008 \pm 0.019$$

$$\int_0^1 \frac{dx}{x} [F_2^p(x) - F_2^n(x)] = \frac{1}{3} + \frac{2}{3} \int_0^1 dx [\bar{u}(x) - \bar{d}(x)]$$

$$\int dx b_1^D(x) = -\frac{5}{6} \lim_{t \rightarrow 0} t F_Q(t) + \frac{1}{18} \int dx [8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D]$$

$$F_2^{\mu p}(x)_{\text{LO}} = x \left[ \frac{4}{9} \{u(x) + \bar{u}(x)\} + \frac{1}{9} \{d(x) + \bar{d}(x)\} + \frac{1}{9} \{s(x) + \bar{s}(x)\} \right]$$

$$\begin{aligned} F_2^{\mu n}(x)_{\text{LO}} &= x \left[ \frac{4}{9} \{u(x) + \bar{u}(x)\} + \frac{1}{9} \{d(x) + \bar{d}(x)\} + \frac{1}{9} \{s(x) + \bar{s}(x)\} \right]_n \\ &= x \left[ \frac{4}{9} \{d(x) + \bar{d}(x)\} + \frac{1}{9} \{u(x) + \bar{u}(x)\} + \frac{1}{9} \{s(x) + \bar{s}(x)\} \right] \end{aligned}$$

$$\frac{1}{x} [F_2^{\mu p}(x)_{\text{LO}} - F_2^{\mu n}(x)_{\text{LO}}] = \frac{3}{9} \{u(x) + \bar{u}(x)\} - \frac{3}{9} \{d(x) + \bar{d}(x)\}$$

$$\begin{aligned} \int_0^1 \frac{dx}{x} [F_2^{\mu p}(x)_{\text{LO}} - F_2^{\mu n}(x)_{\text{LO}}] &= \int_0^1 dx \left[ \frac{1}{3} \{u_v(x) + 2\bar{u}(x)\} - \frac{1}{3} \{d_v(x) + 2\bar{d}(x)\} \right] \\ &= \frac{2}{3} - \frac{1}{3} + \frac{2}{3} \int_0^1 dx [\bar{u}(x) - \bar{d}(x)] \end{aligned}$$

Extrapolating the NMC data, they obtained

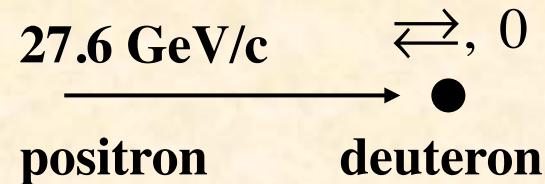
$$S_G = 0.235 \pm 0.026$$

30% is missing!  $\Rightarrow \bar{u} < \bar{d}$  ?

As the Gottfried-sum-rule violation indicated  $\bar{u} < \bar{d}$ ,  
the  $b_1$ -sum-rule violation suggests  
a finite tensor polarization for antiquarks ( $\delta_T \bar{u} \neq 0$ ).

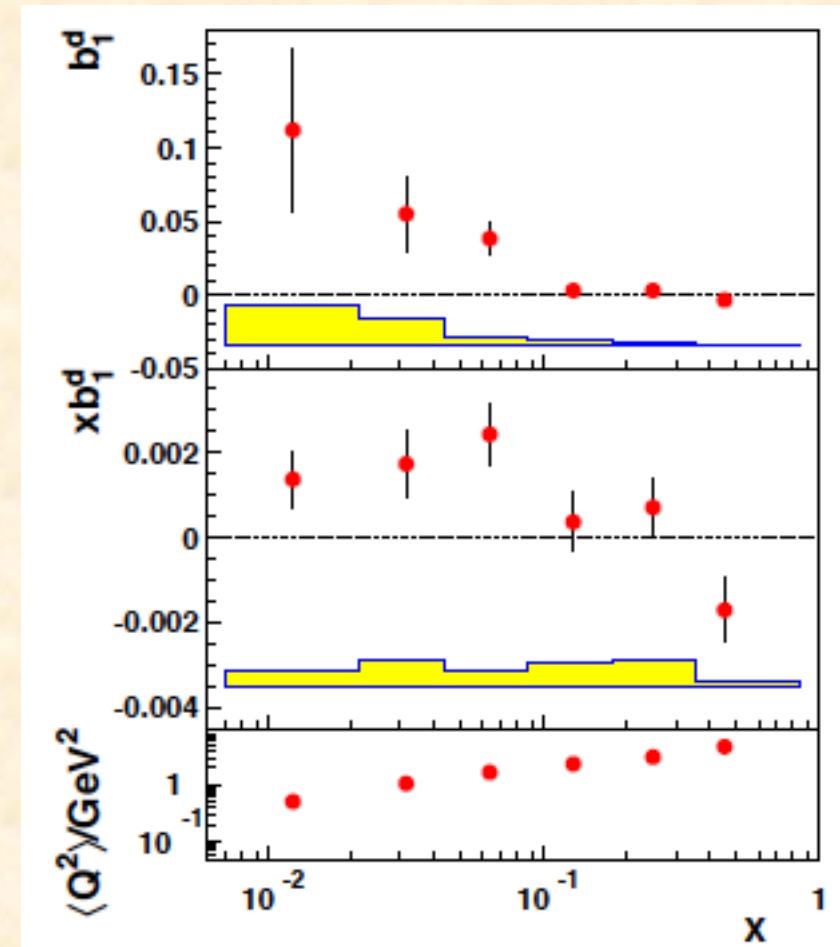
# HERMES measurements on $b_1$

A. Airapetian *et al.* (HERMES), PRL 95 (2005) 242001.

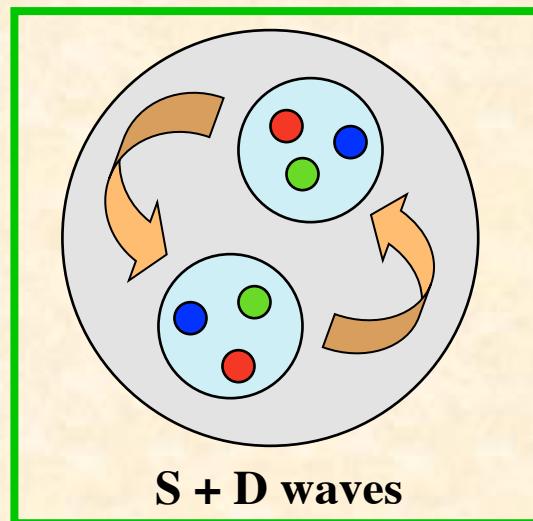


$b_1$  measurements in the kinematical region

$0.01 < x < 0.45, 0.5 \text{ GeV}^2 < Q^2 < 5 \text{ GeV}^2$



# Standard convolution description for the deuteron



standard model

W. Cosyn, Yu-Bing Dong, SK, M. Sargsian,  
to be submitted for publication.

# Standard convolution approach

**Convolution model:**  $A_{hH,hH}(x) = \int \frac{dy}{y} \sum_s f_s^H(y) \hat{A}_{hs,hs}(x/y) \equiv \sum_s f_s^H(y) \otimes \hat{A}_{hs,hs}(y)$

$$A_{hH,h'H'} = \epsilon_{h'}^{*\mu} W_{\mu\nu}^{H'H} \epsilon_h^\nu, \quad b_1 = A_{+0,+0} - \frac{A_{++,++} + A_{+-,+-}}{2},$$

$$\hat{A}_{+\uparrow,\uparrow} = F_1 - g_1, \quad \hat{A}_{+\downarrow,\downarrow} = F_1 + g_1$$

**Momentum distribution:**  $f^H(y) = \int d^3 p |\phi^H(\vec{p})|^2 \delta\left(y - \frac{E + p_z}{M}\right)$

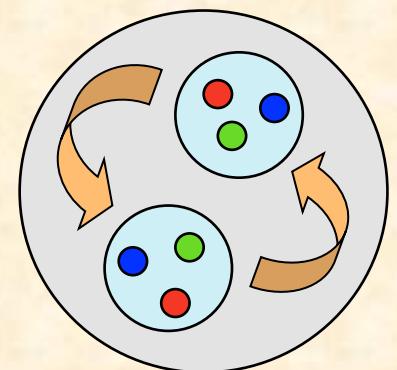
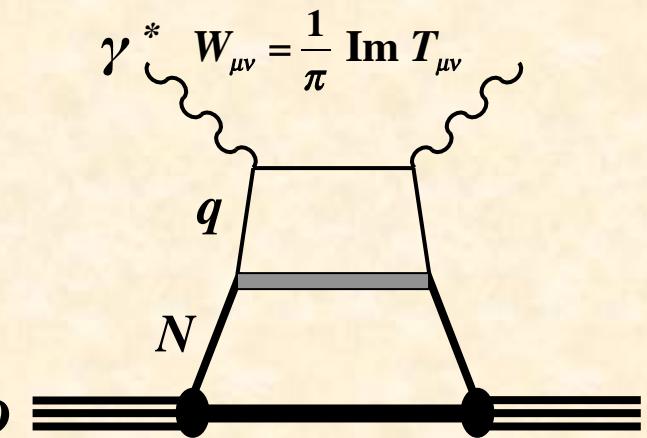
$$f^H(y) \equiv f_\uparrow^H(y) + f_\downarrow^H(y)$$

**D-state admixture:**  $\phi^H(\vec{p}) = \phi_{\ell=0}^H(\vec{p}) + \phi_{\ell=2}^H(\vec{p})$

$$b_1(x) = \frac{1}{2} \int \frac{dy}{y} \sum_{i=p,n} \left[ f^0(y) - \frac{f^+(y) + f^-(y)}{2} \right] F_1(x/y) = \int \frac{dy}{y} \delta f_T(y) F_1(x/y)$$

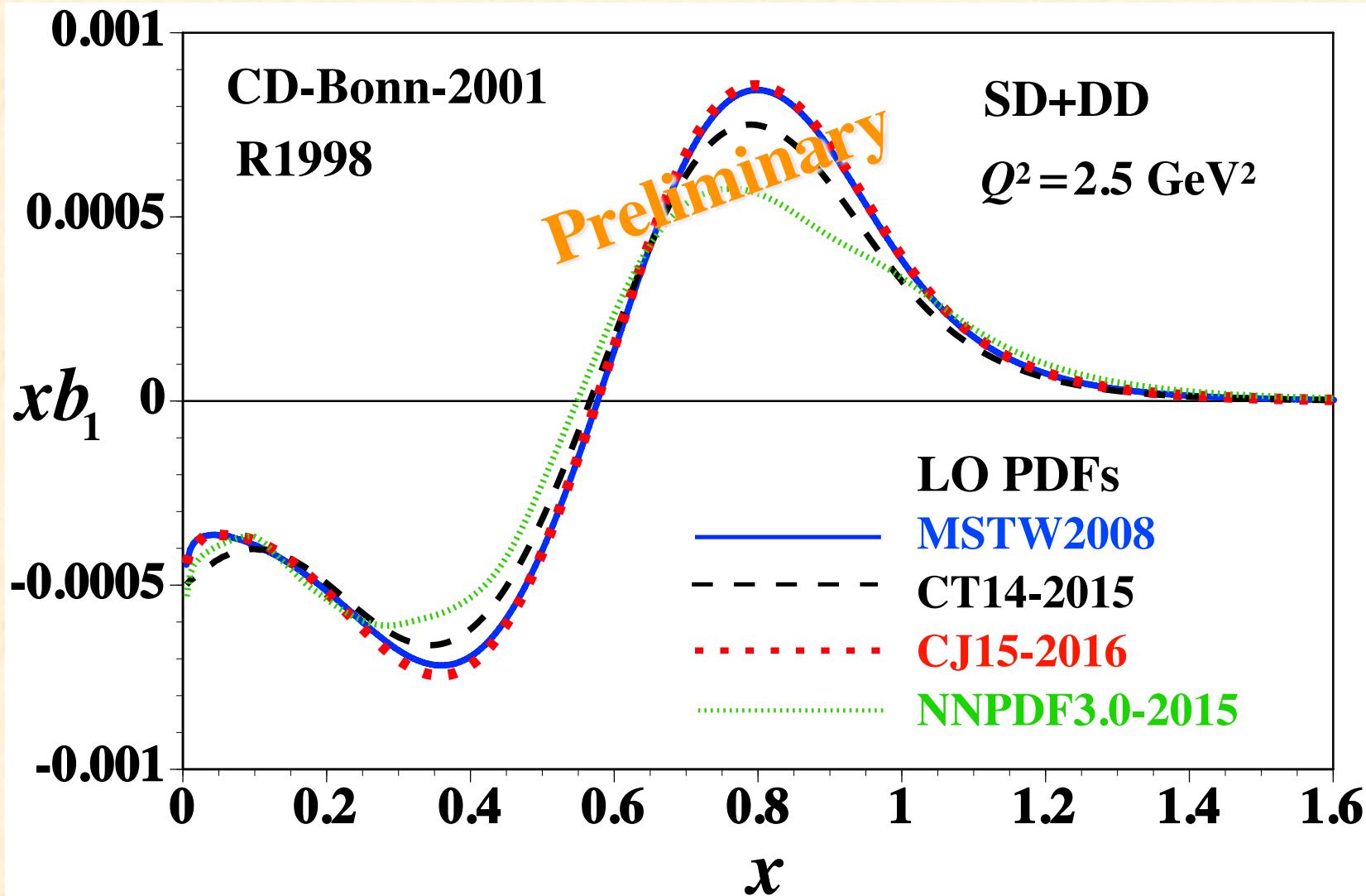
$$\delta_T f(y) = \int d^3 p y \left[ -\frac{3}{4\sqrt{2}\pi} \phi_0(p) \phi_2(p) + |\phi_2(p)|^2 \frac{3}{16\pi} \right] (3 \cos^2 \theta - 1) \delta\left(y - \frac{\vec{p} \cdot \vec{q}}{Mv}\right)$$

Standard model  
of the deuteron



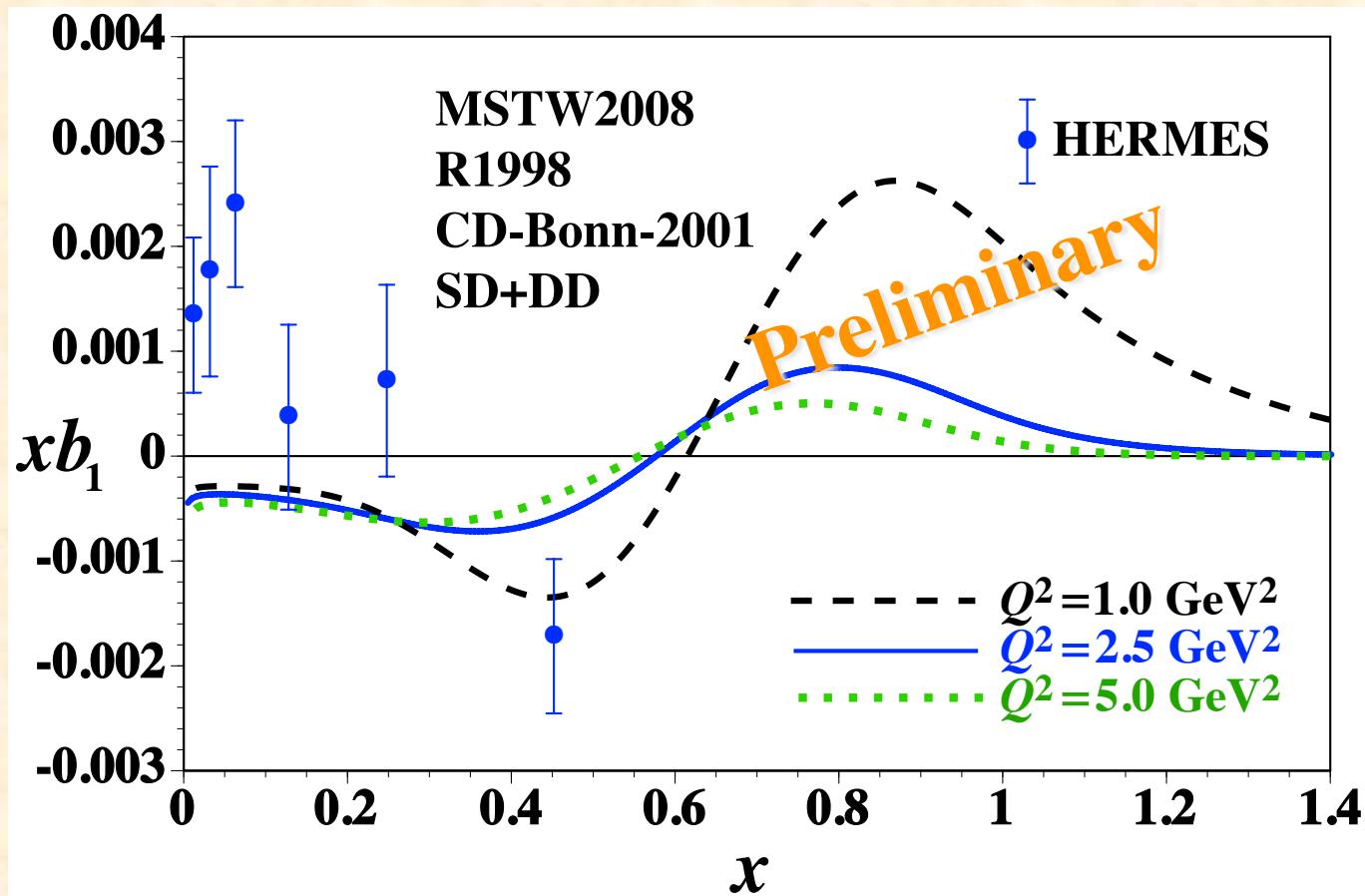
S + D waves

# Results on $b_1$ : used PDF dependence



# Comparison with HERMES measurements

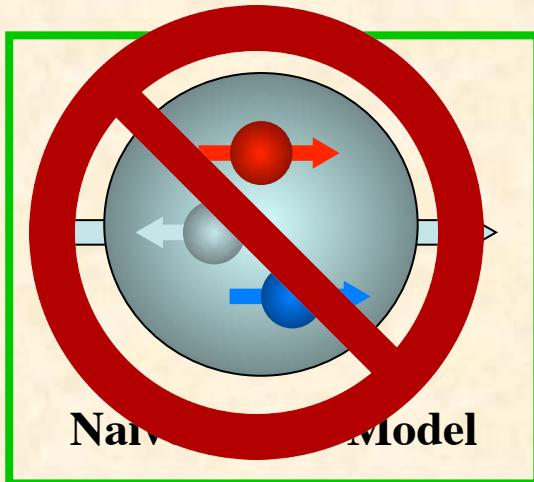
W. Cosyn, Yu-Bing Dong, SK, M. Sargsian, ..



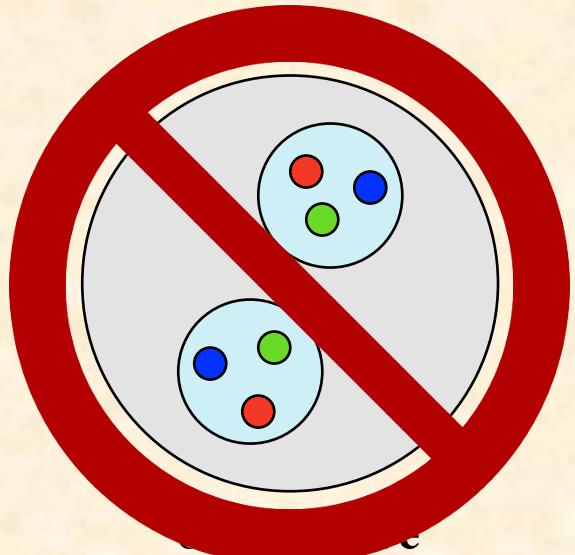
$|b_1(\text{theory})| \ll |b_1(\text{HERMES})|$

Standard convolution model does not  
work for the deuteron tensor structure!?

# Summary I

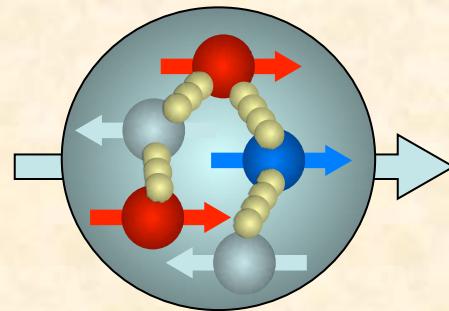


“old” standard model



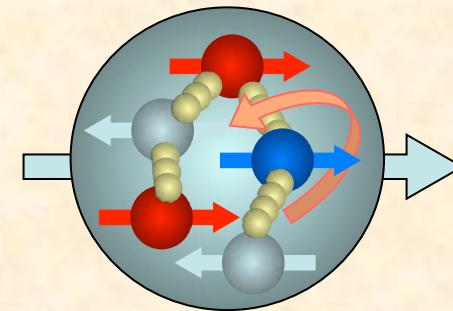
$$b_1 = 0$$

## Nucleon spin



Sea-quarks and gluons?

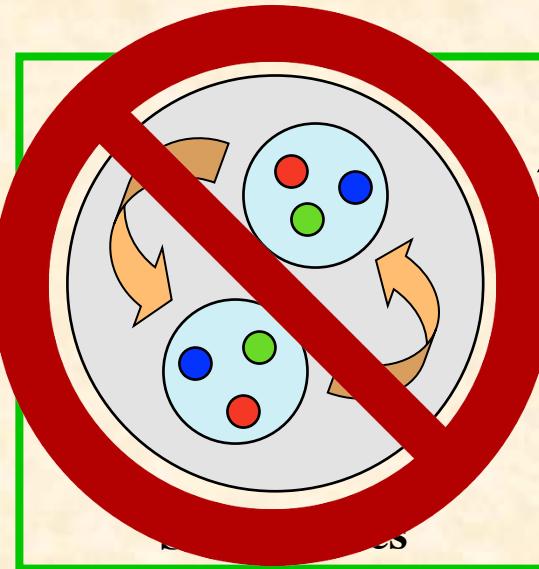
## Nucleon spin puzzle



Orbital angular momenta ?

We have shown in this work  
that the standard deuteron model  
does not work!  
→ new hadron physics??

## Tensor structure



standard model     $b_1 \neq 0$

Tensor-structure puzzle?  
?

$b_1^{\text{experiment}}$   
 $\neq b_1^{\text{"standard model"}}$

# JLab PAC-38 (Aug. 22-26, 2011) proposal, PR12-11-110

## The Deuteron Tensor Structure Function $b_1$

A Proposal to Jefferson Lab PAC-38.  
(Update to LOI-11-003)

J.-P. Chen (co-spokesperson), P. Solvignon (co-spokesperson),  
K. Allada, A. Camsonne, A. Deur, D. Gaskell,  
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Donal B. Day, Hovhannes Baghdasaryan, Charles Hanretty  
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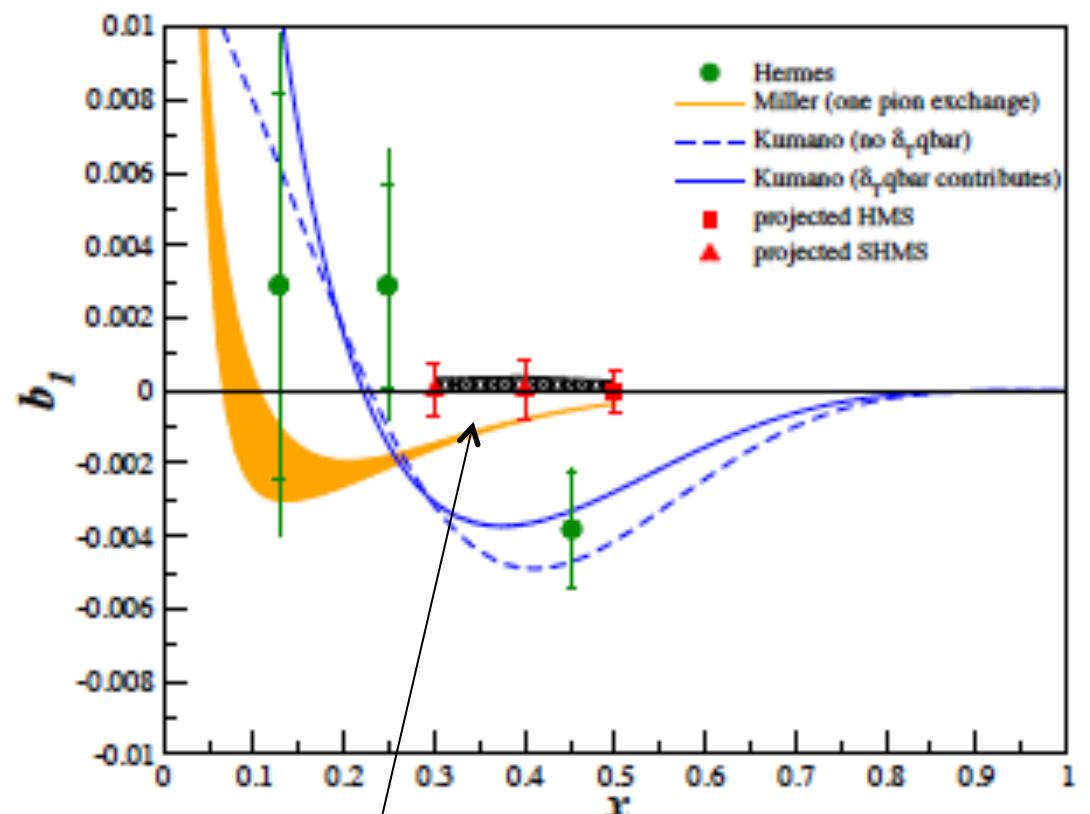
W. Bertozzi, S. Gilad,  
A. Kelleher, V. Sulkosky  
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Seonho Choi, Hoyoung Kang, Hyekoo Kang, Yoomin Oh  
*Seoul National University, Seoul 151-747 Korea*

# Approved!

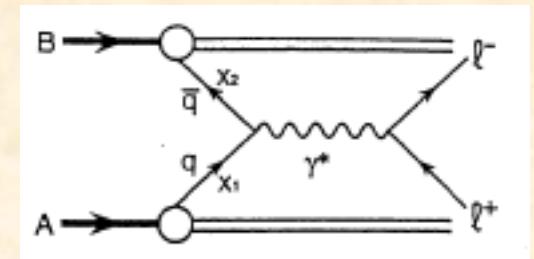
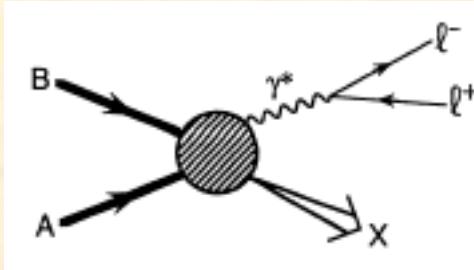


Expected errors  
by JLab

# Possible Fermilab experiment at Main Injector



# Drell-Yan process for ubar – dbar (current E906 experiment)



$$d\sigma^{AB} \propto \sum_i e_i^2 \left[ q_i^A(x_1, q^2) \bar{q}_i^B(x_2, q^2) + \bar{q}_i^A(x_1, q^2) q_i^B(x_2, q^2) \right] \quad q^2 = m_{\mu\mu}^2$$

$$d\sigma^{pp} \propto \frac{4}{9} [u(x_1)\bar{u}(x_2) + \bar{u}(x_1)u(x_2)] + \frac{1}{9} [d(x_1)\bar{d}(x_2) + \bar{d}(x_1)d(x_2)] + \frac{1}{9} [s(x_1)\bar{s}(x_2) + \bar{s}(x_1)s(x_2)]$$

$$d\sigma^{pn} \propto \frac{4}{9} [u(x_1)\bar{d}(x_2) + \bar{u}(x_1)d(x_2)] + \frac{1}{9} [d(x_1)\bar{u}(x_2) + \bar{d}(x_1)u(x_2)] + \frac{1}{9} [s(x_1)\bar{s}(x_2) + \bar{s}(x_1)s(x_2)]$$

At large  $x_F = x_1 - x_2$  ( $x_1 \rightarrow 1, x_2 \rightarrow 0$ )

$\bar{u}(x_1), \bar{d}(x_1), \bar{s}(x_1) \ll u(x_1), d(x_1) \rightarrow u_v(x_1), d_v(x_1)$

$$d\sigma^{pp} - d\sigma^{pn} \propto \frac{4}{9} [u_v(x_1) \{ \bar{u}(x_2) - \bar{d}(x_2) \}] - \frac{1}{9} [d_v(x_1) \{ \bar{u}(x_2) - \bar{d}(x_2) \}]$$

$$d\sigma^{pp} + d\sigma^{pn} \propto \frac{4}{9} [u_v(x_1) \{ \bar{u}(x_2) + \bar{d}(x_2) \}] + \frac{1}{9} [d_v(x_1) \{ \bar{u}(x_2) + \bar{d}(x_2) \}] + \frac{2}{9} [s(x_1)\bar{s}(x_2)]$$

$$A_{DY} = \frac{d\sigma^{pp} - d\sigma^{pn}}{d\sigma^{pp} + d\sigma^{pn}} \rightarrow \frac{\{4u_v(x_1) - d_v(x_1)\}\{\bar{u}(x_2) - \bar{d}(x_2)\}}{\{4u_v(x_1) + d_v(x_1)\}\{\bar{u}(x_2) + \bar{d}(x_2)\}}$$

at large  $x_F$

**$\bar{u} - \bar{d}$  determination**

$$\text{Roughly, } \frac{2\sigma^{pd}}{\sigma^{pp}} \sim 1 + \frac{1}{2} \left[ \frac{\bar{d}(x_2)}{\bar{u}(x_2)} - 1 \right] \quad \text{at large } x_F$$

# Flavor dependence of antiquark distributions

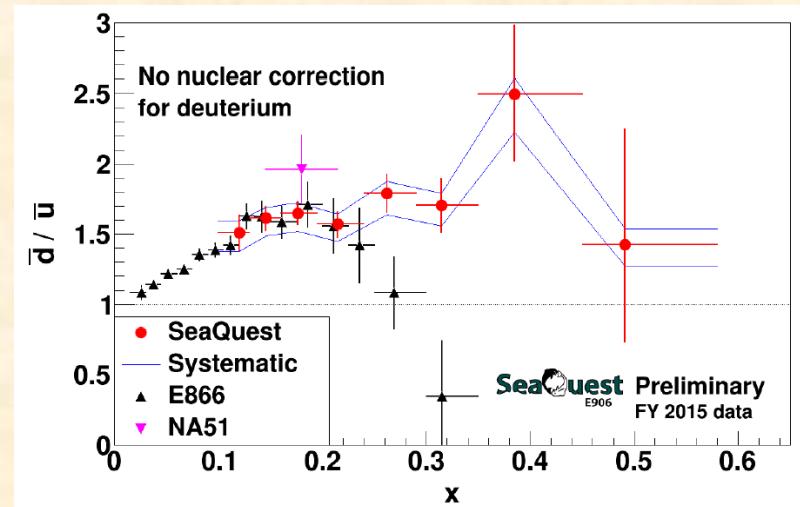
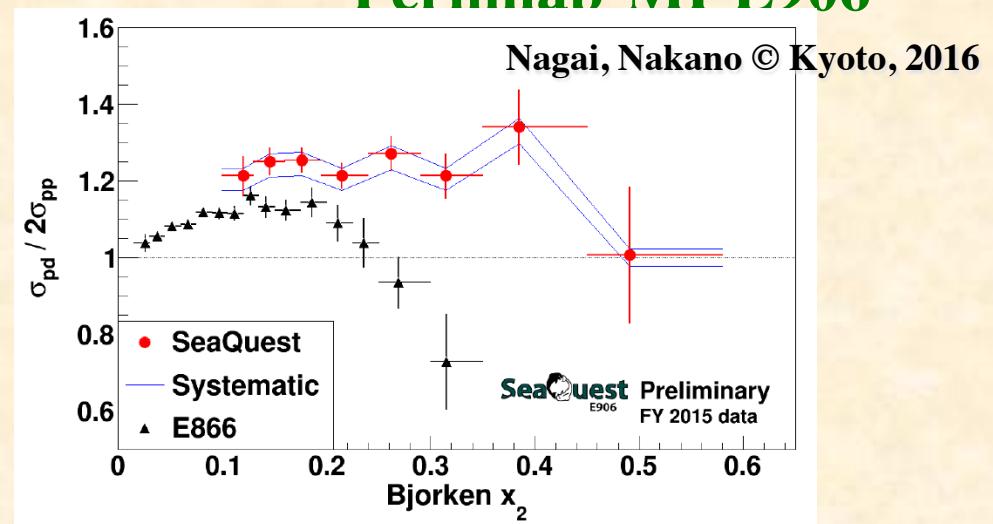
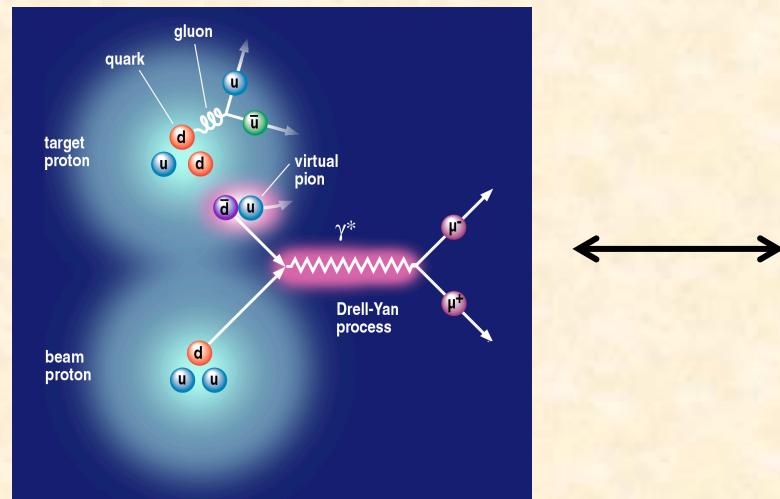
Gottfried sum:  $S_G = \int_0^1 \frac{dx}{x} [F_2^{\mu p}(x) - F_2^{\mu n}(x)] = \frac{1}{3} + \frac{2}{3} \int_0^1 dx [\bar{u}(x) - \bar{d}(x)]$

$S_G(\text{experiment}) = 0.235 \pm 0.026$

Fermilab-MI-E906

S. Kumano, Phys. Rept. 303 (1998) 183;  
 G. T. Garvey and J.-C. Peng,  
 Prog. Part. Nucl. Phys. 47 (2001) 203;  
 J.-C. Peng and J.-W. Qiu,  
 Prog. Part. Nucl. Phys. 76 (2014) 43.

$$\frac{2\sigma^{pd}}{\sigma^{pp}} \sim 1 + \frac{1}{2} \left[ \frac{\bar{d}(x_2)}{\bar{u}(x_2)} - 1 \right] \text{ at large } x_F$$



# Theoretical estimation on tensor-polarization asymmetry

# Experimental possibility at Fermilab

E1039

## Polarized fixed-target experiments at the Main Injector



© Fermilab

Drell-Yan experiment with a polarized proton target

Co-Spokespersons: A. Klein, X. Jiang, Los Alamos National Laboratory

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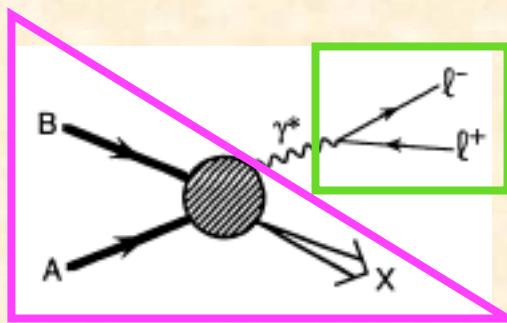
# Drell-Yan cross section and hadron tensor

$$d\sigma = \frac{1}{4\sqrt{(P_A \cdot P_B)^2 - M_A^2 M_B^2}} \sum_{S_r} \sum_{S_{r^+}} (2\pi)^4 \delta^4(P_A + P_B - k_{r^+} - k_{r^-} - P_X) \left| \langle l^+ l^- X | T | AB \rangle \right|^2 \frac{d^3 k_{r^+}}{(2\pi)^3 2E_{r^+}} \frac{d^3 k_{r^-}}{(2\pi)^3 2E_{r^-}}$$

$$\langle l^+ l^- X | T | AB \rangle = \bar{u}(k_{r^-}, \lambda_{r^-}) e \gamma_\mu v(k_{r^+}, \lambda_{r^+}) \frac{g^{\mu\nu}}{(k_{r^+} + k_{r^-})^2} \langle X | e J_\nu(0) | AB \rangle$$

$$\frac{d\sigma}{d^4 Q d\Omega} = \frac{\alpha^2}{2sQ^4} L_{\mu\nu} W^{\mu\nu}$$

$$W^{\mu\nu} \equiv \int \frac{d^4 \xi}{(2\pi)^4} e^{iQ \cdot \xi} \langle P_A S_A P_B S_B | J^\mu(0) J^\nu(\xi) | P_A S_A P_B S_B \rangle$$

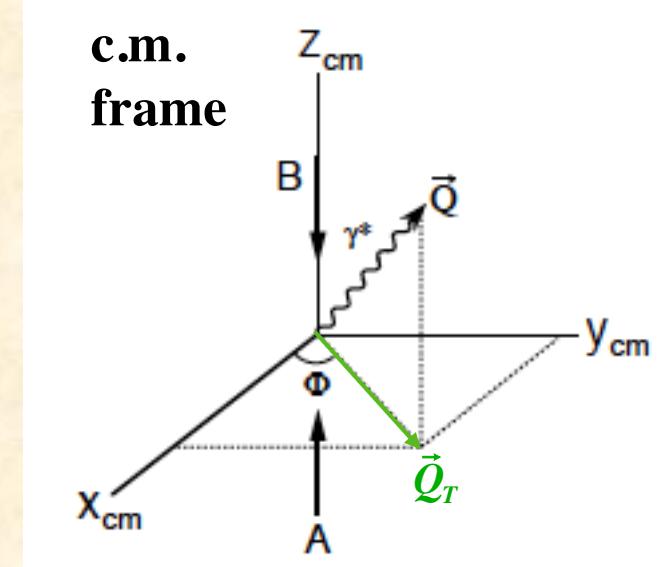


For the details, see

- M. Hino and SK, Phys. Rev. D59 (1999) 094026.
- M. Hino and SK, Phys. Rev. D60 (1999) 054018.

# Formalism of $pd$ Drell-Yan process

See Ref. PRD59  
(1999) 094026.



proton-proton      proton-deuteron

Number of  
structure functions

48

108

After integration over  $\vec{Q}_T$   
(or  $\vec{Q}_T \rightarrow 0$ )

11

22

In parton model

3

4

Additional structure  
functions due to  
tensor structure

I explain  
in the next page.

# Spin asymmetries in the parton model

unpolarized:  $q_a$ ,

longitudinally polarized:  $\Delta q_a$ ,

transversely polarized:  $\Delta_T q_a$ ,

tensor polarized:  $\delta q_a$

## Unpolarized cross section

$$\left\langle \frac{d\sigma}{dx_A dx_B d\Omega} \right\rangle = \frac{\alpha^2}{4Q^2} (1 + \cos^2 \theta) \frac{1}{3} \sum_a e_a^2 [ q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B) ]$$

## Spin asymmetries

$$A_{LL} = \frac{\sum_a e_a^2 [\Delta q_a(x_A) \Delta \bar{q}_a(x_B) + \Delta \bar{q}_a(x_A) \Delta q_a(x_B)]}{\sum_a e_a^2 [q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B)]}$$

$$A_{TT} = \frac{\sin^2 \theta \cos(2\phi)}{1 + \cos^2 \theta} \frac{\sum_a e_a^2 [\Delta_T q_a(x_A) \Delta_T \bar{q}_a(x_B) + \Delta_T \bar{q}_a(x_A) \Delta_T q_a(x_B)]}{\sum_a e_a^2 [q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B)]}$$

$$A_{UQ_0} = \frac{\sum_a e_a^2 [q_a(x_A) \delta_T \bar{q}_a(x_B) + \bar{q}_a(x_A) \delta_T q_a(x_B)]}{2 \sum_a e_a^2 [q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B)]}$$

$$A_{LT} = A_{TL} = A_{UT} = A_{TU} = A_{TQ_0} = A_{UQ_1} \\ = A_{LQ_1} = A_{TQ_1} = A_{UQ_2} = A_{LQ_2} = A_{TQ_2} = 0$$

## Advantage of the hadron reaction ( $\delta \bar{q}$ measurement)

$$A_{UQ_0} (\text{large } x_F) \approx \frac{\sum_a e_a^2 q_a(x_A) \delta_T \bar{q}_a(x_B)}{2 \sum_a e_a^2 q_a(x_A) \bar{q}_a(x_B)}$$

Note:  $\delta \neq \text{transversity}$  in my notation

# Functional form of parametrization

Assume flavor-symmetric antiquark distributions:  $\delta_T \bar{q}^D \equiv \delta_T \bar{u}^D = \delta_T \bar{d}^D = \delta_T s^D = \delta_T \bar{s}^D$

$$b_1^D(x)_{LO} = \frac{1}{18} [ 4\delta_T u_v^D(x) + \delta_T d_v^D(x) + 12 \delta_T \bar{q}^D(x) ]$$

At  $Q_0^2 = 2.5 \text{ GeV}^2$ ,  $\delta_T q_v^D(x, Q_0^2) = \delta_T w(x) q_v^D(x, Q_0^2)$ ,  $\delta_T \bar{q}^D(x, Q_0^2) = \alpha_{\bar{q}} \delta_T w(x) \bar{q}^D(x, Q_0^2)$

Certain fractions of quark and antiquark distributions are tensor polarized and such probabilities are given by the function  $\delta_T w(x)$  and an additional constant  $\alpha_{\bar{q}}$  for antiquarks in comparison with the quark polarization.

$$\begin{aligned} b_1^D(x, Q_0^2)_{LO} &= \frac{1}{18} [ 4\delta_T u_v^D(x, Q_0^2) + \delta_T d_v^D(x, Q_0^2) + 12 \delta_T \bar{q}^D(x, Q_0^2) ] \\ &= \frac{1}{36} \delta_T w(x) [ 5 \{ u_v(x, Q_0^2) + d_v(x, Q_0^2) \} + 4a_{\bar{q}} \{ 2\bar{u}(x, Q_0^2) + 2\bar{d}(x, Q_0^2) + s(x, Q_0^2) + \bar{s}(x, Q_0^2) \} ] \end{aligned}$$

$$\delta_T w(x) = ax^b(1-x)^c(x_0 - x)$$

Two types of analyses

**Set 1:**  $\delta_T \bar{q}^D(x) = 0$  Tensor-polarized antiquark distributions are terminated ( $\alpha_{\bar{q}} = 0$ ),

**Set 2:**  $\delta_T \bar{q}^D(x) \neq 0$  Finite tensor-polarized antiquark distributions are allowed ( $\alpha_{\bar{q}} \neq 0$ ).

# Results

SK, PRD 82 (2010) 017501

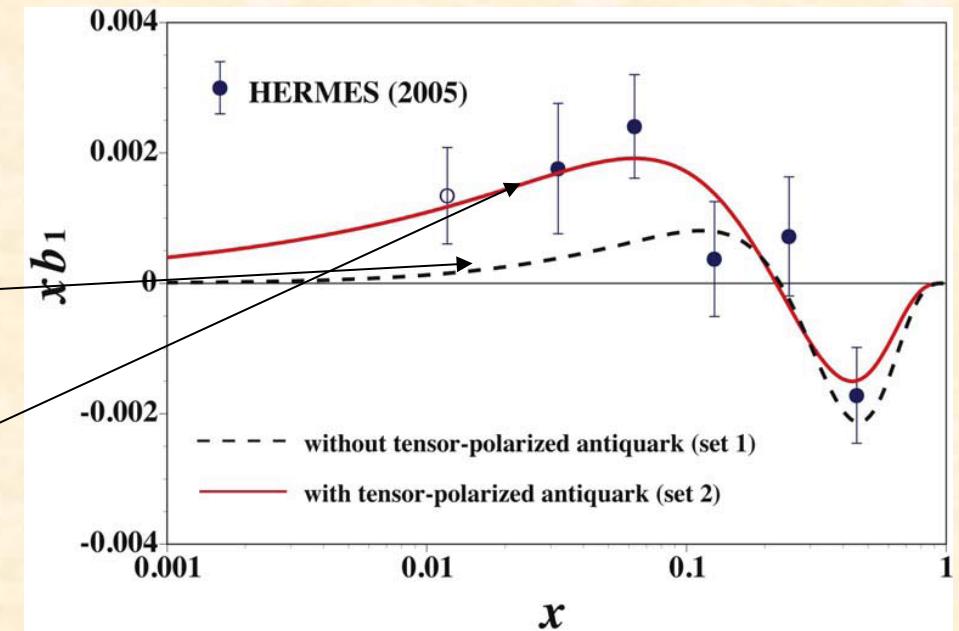
Two-types of fit results:

- set-1:  $\chi^2 / \text{d.o.f.} = 2.83$

Without  $\delta_T q$ , the fit is not good enough.

- set-2:  $\chi^2 / \text{d.o.f.} = 1.57$

With finite  $\delta_T q$ , the fit is reasonably good.



Obtained tensor-polarized distributions

$\delta_T q(x)$ ,  $\delta_T \bar{q}(x)$  from the HERMES data.

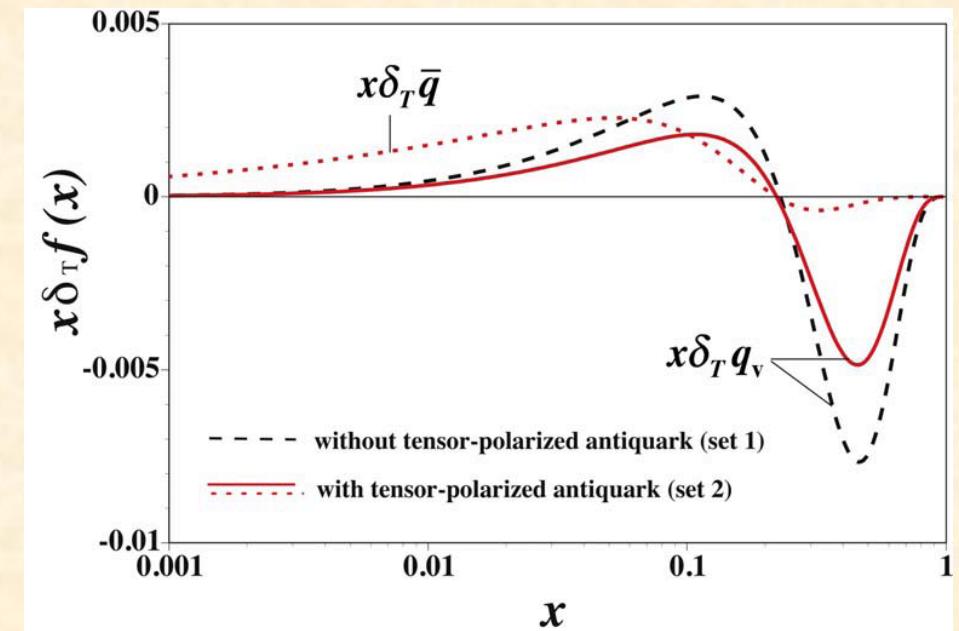
→ They could be used for

- experimental proposals,
- comparison with theoretical models.

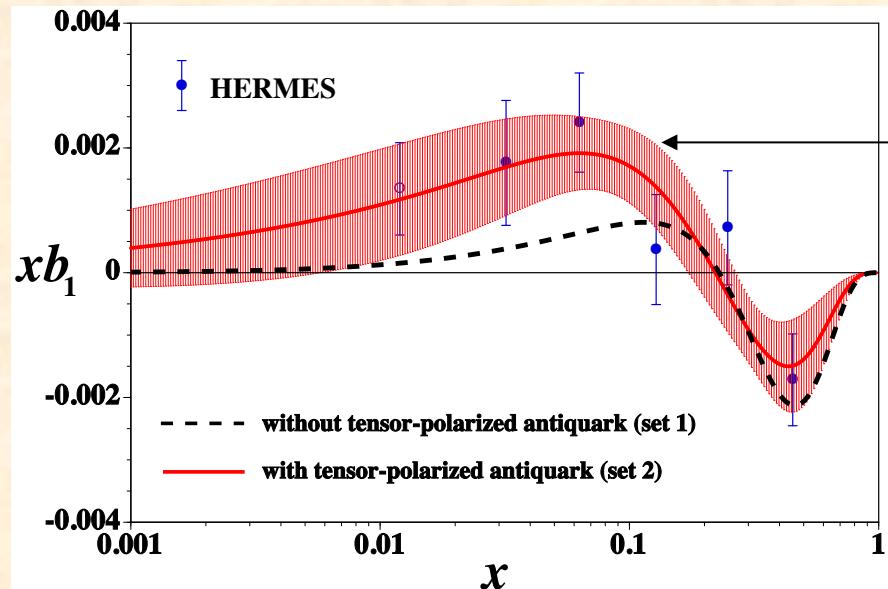
Finite tensor polarization for antiquarks:

$$\int_0^1 dx b_1(x) = 0.058$$

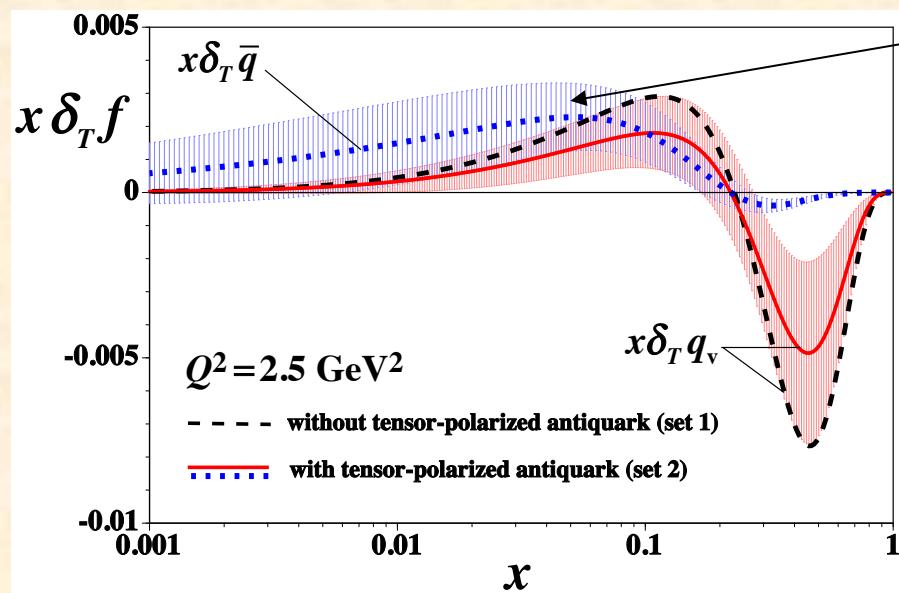
$$= \frac{1}{9} \int_0^1 dx [4\delta_T \bar{u}(x) + \delta_T \bar{d}(x) + \delta_T \bar{s}(x)]$$



# Tensor-polarized PDFs with errors



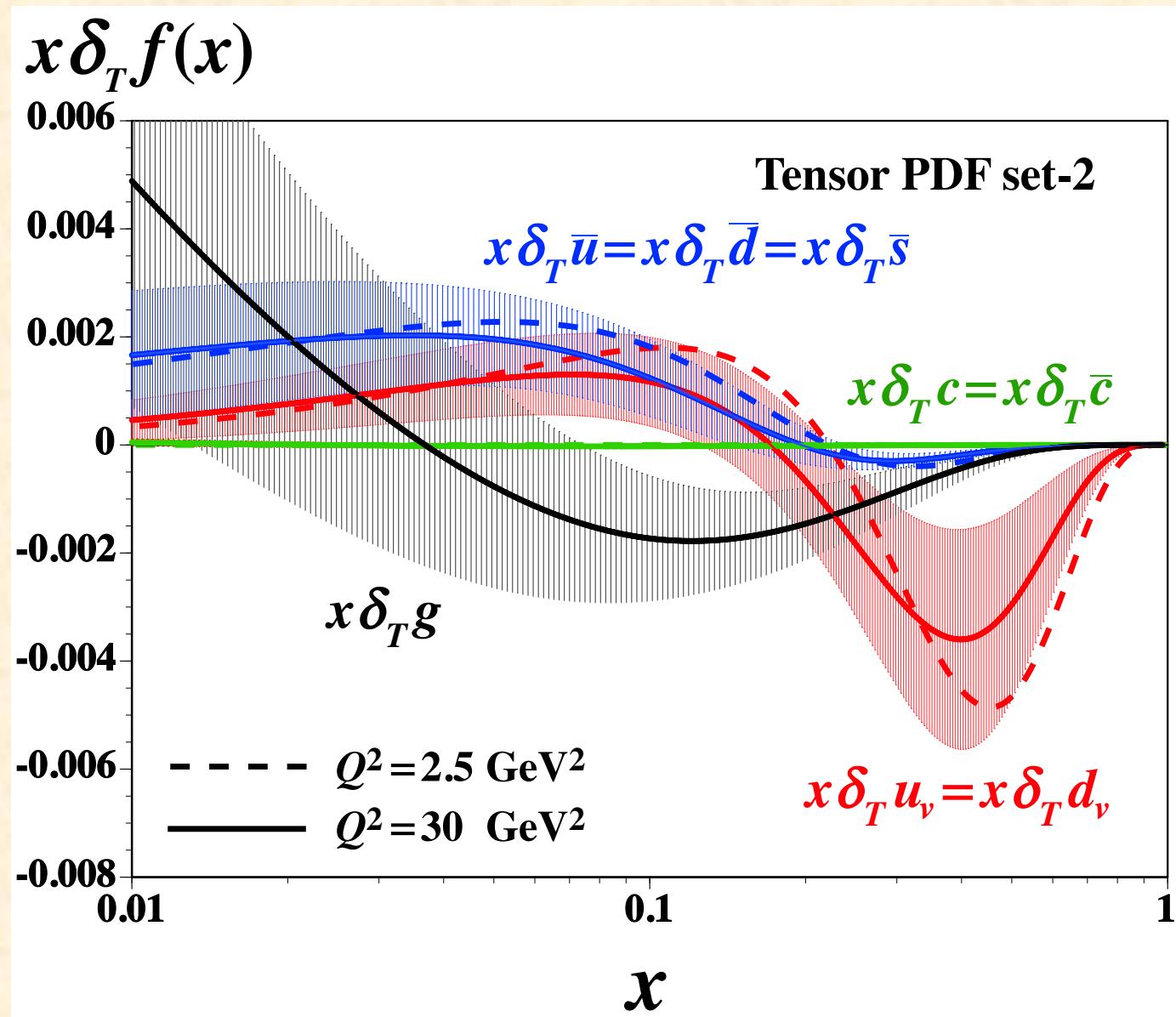
still large errors,  
need experimental improvement  
→ JLab, EIC, ...



experimental measurement  
for antiquark distributions  
→ Fermilab, ...

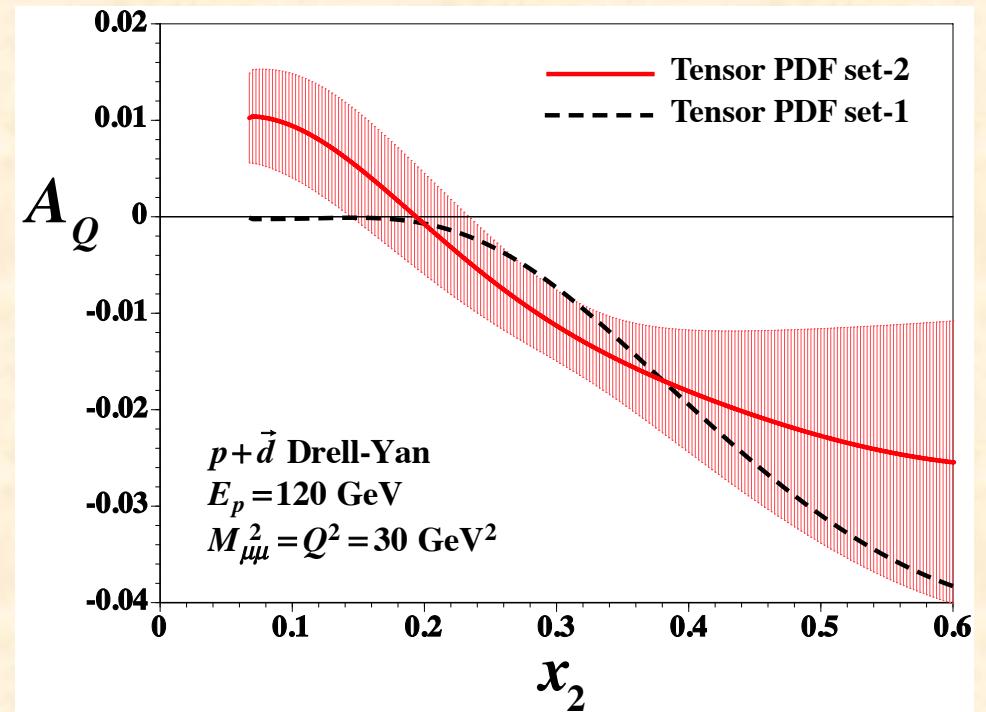
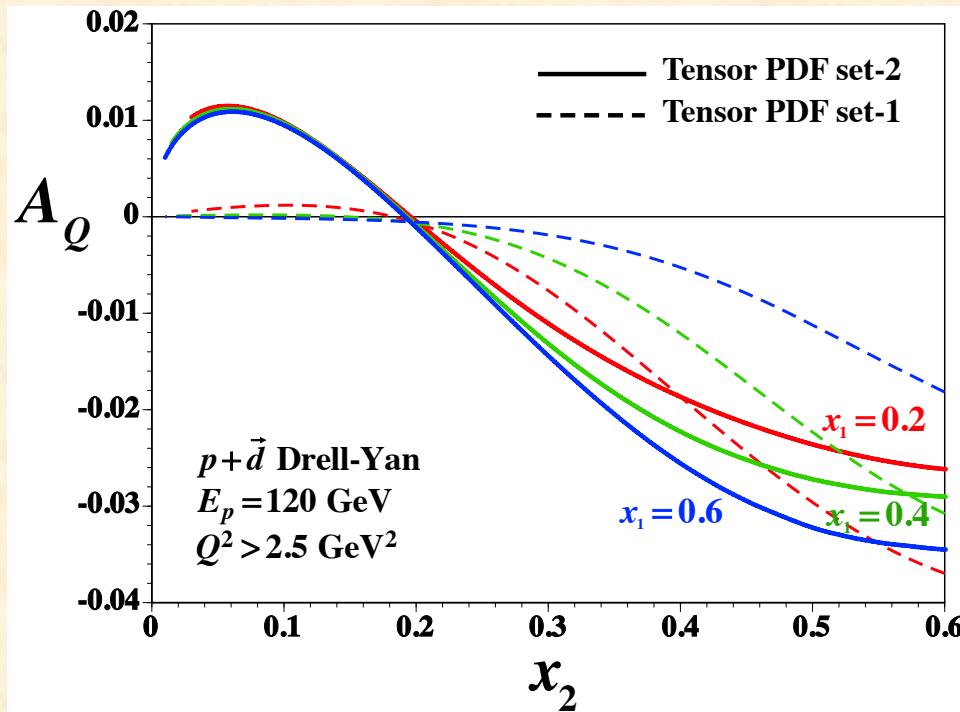
# $Q^2$ evolution

$Q^2 = 2.5 \text{ GeV}^2 \rightarrow 30 \text{ GeV}^2$



# Tensor-polarized spin asymmetry

$$A_Q \equiv 2A_{UQ_0} = \frac{\sum_a e_a^2 [q_a(x_A) \delta_T \bar{q}_a(x_B) + \bar{q}_a(x_A) \delta_T q_a(x_B)]}{\sum_a e_a^2 [q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B)]}$$



# Experimental possibilities

Approved experiment! (2019~)



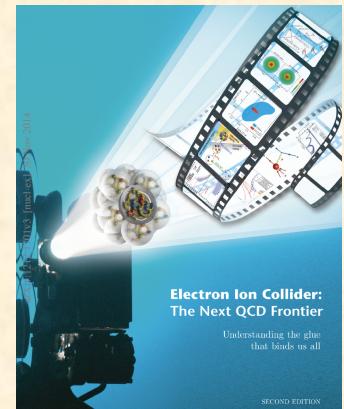
© JLab

E1039 proposal



© Fermilab

EIC (arXiv:1212.1701)



Linear Collider  
(with fixed target)



Possibilities: Spin-1 projects are possible in principle  
at other hadron facilities.



© BNL



© J-PARC



© GSI



© CERN-COMPASS



© IHEP, Russia

## Summary II

JLab PR12-11-110 (2019~) :  $b_1 = \frac{1}{2} \sum_i e_i^2 (\delta_T q_i + \delta_T \bar{q}_i)$

No separation between  $\delta_T q$  and  $\delta_T \bar{q}$

Fermiab E1039 (20xx) :  $A_Q$  (large  $x_F$ )  $\approx \frac{\sum_a e_a^2 q_a(x_1) \delta_T \bar{q}_a(x_2)}{2 \sum_a e_a^2 q_a(x_1) \bar{q}_a(x_2)}$

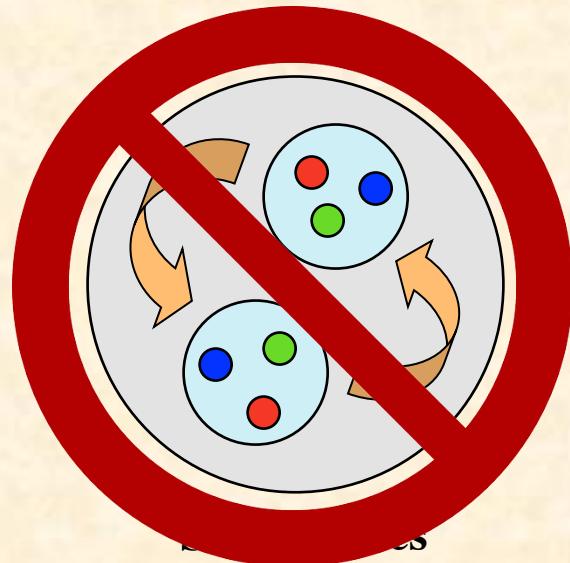
Separation of  $\delta_T \bar{q}$

→ possible new exotic hadron physics mechanism

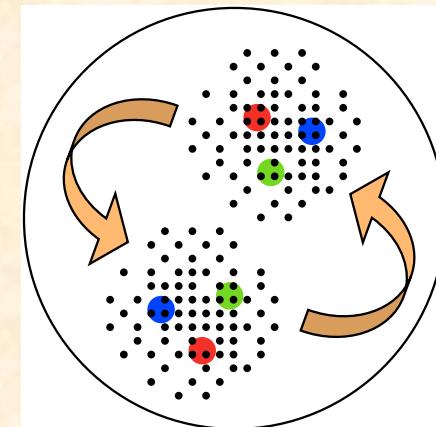
# Summary III

## Spin-1 structure functions of the deuteron

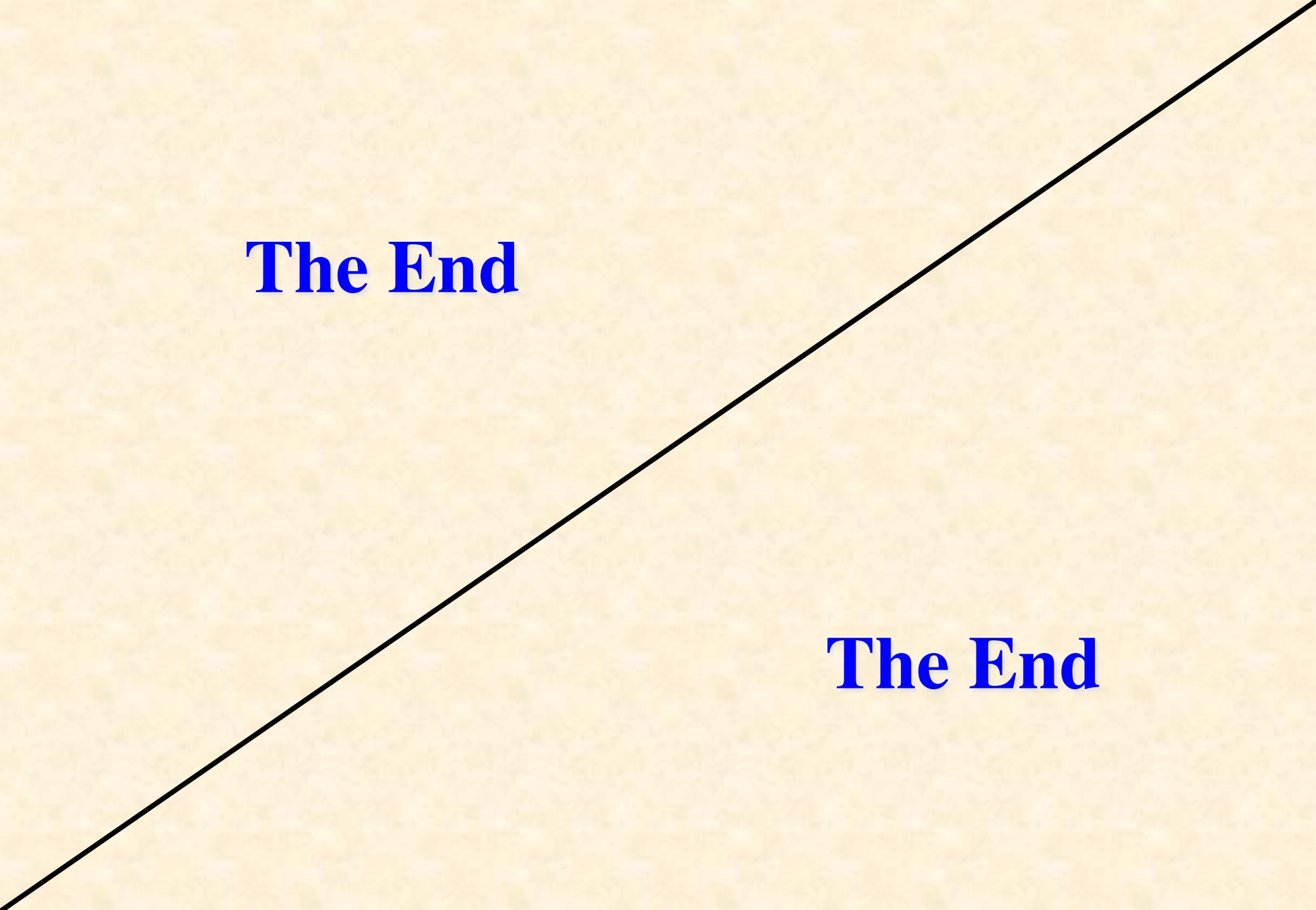
- new spin structure
- tensor structure in quark-gluon degrees of freedom
- new exotic signature in hadron-nuclear physics?
- experiments: Jlab (approved), Fermilab, ... , EIC, ILC, ...
- **Fermilab E1039 → new discovery on tensor-polarized antiquark distributions (my talk today)**



standard model



? new exotic  
mechanism?



**The End**

**The End**

# Recent work: Pion, Hidden-color, Six-quark

G. A. Miller,  
PRC 89 (2014) 045203.

$$|6q\rangle = |NN\rangle + |\Delta\Delta\rangle + |CC\rangle + \dots$$

